

## **Lagrangian Turbulence and Transport in Semi-enclosed Basins and Coastal Regions**

Annalisa Griffa

Division of Meteorology and Physical Oceanography  
Rosenstiel School of Marine and Atmospheric Science  
4600 Rickenbacker Causeway, Miami, Florida 33149  
phone: 305 421 4816, fax: 305 421 4696, email: [agriffa@rsmas.miami.edu](mailto:agriffa@rsmas.miami.edu)

Tamay M. Özgökmen

phone: 305 421 4053, fax: 305 421 4696, email: [tozgokmen@rsmas.miami.edu](mailto:tozgokmen@rsmas.miami.edu)

Award: # N00014-05-1-0094

<http://www.rsmas.miami.edu/LAPCOD/research/>

### **LONG-TERM GOALS**

The long-term goal of this project is the development and application of new methods of investigation for the use of Lagrangian data and other emerging in-situ and remote instruments (drifters, gliders, HF radar and satellite) that provide information on upper ocean advection. Special attention is given to the development of new techniques for data fusion and assimilation of data in Eulerian numerical models, with focus on coastal flows.

### **OBJECTIVES**

The project has the following specific objectives:

- 1) To test the impact of Lagrangian data assimilation of Argo float trajectories in the framework of operational models
- 2) To develop and test new methods for assimilation and fusion of tracer data with numerical model outputs.
- 3) To investigate and improve prediction of upper ocean fronts in coastal areas.

### **APPROACH**

The work involves a combination of analytical, numerical and data processing techniques. The method development has been carried out in collaboration with L. Piterbarg (USC), A. Molcard (LSEET Université' of Toulon), V. Taillandier (CNRS, Paris), E. Zambianchi (Naples Univ., Italy), N. Pinardi (INGV, Italy).

### **WORK COMPLETED**

- 1) Publication of a paper on particle spreading using drifters and HF radar data (Molcard et al., 2009).

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>2009</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2009 to 00-00-2009</b>	
4. TITLE AND SUBTITLE <b>Lagrangian Turbulence and Transport in Semi-enclosed Basins and Coastal Regions</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of Miami,Rosenstiel School of Marine and Atmospheric Science,4600 Rickenbacker Causeway,Miami,FL,33149</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>10</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

2) Submission and final revision of a paper on assimilation of Argo floats in an operational model system (Taillandier et al., 2009)

3) Submission of a paper on tracer data fusion with numerical model outputs (Mercatini et al., 2009)

4) Submission of a paper on the dynamics of coastal buoyancy plumes and instabilities (Magaldi et al., 2009)

## RESULTS

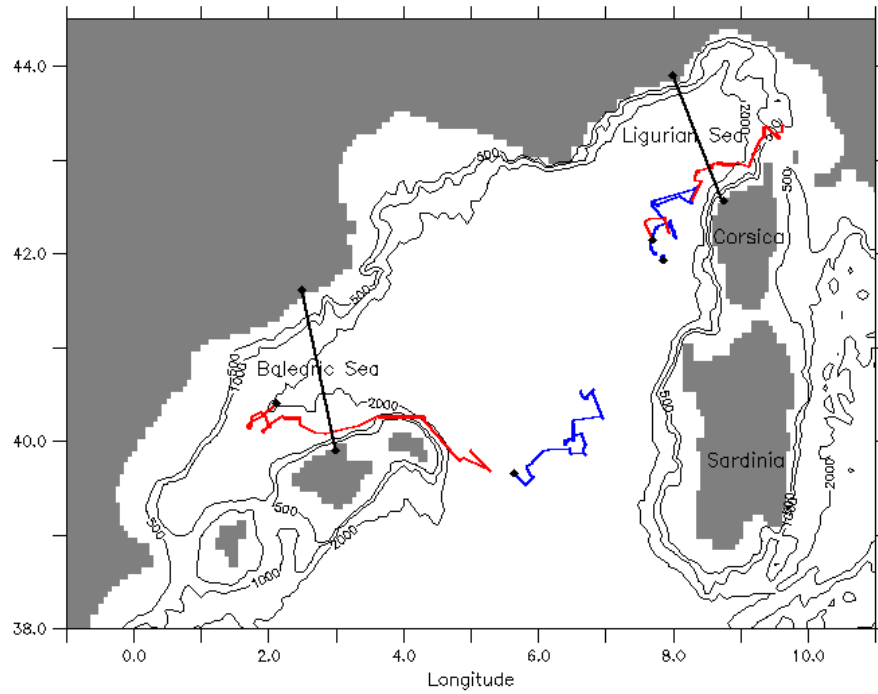
### *i) Assimilation of Argo float trajectories in the framework of an operational system and impact on the regional circulation analysis*

The Lagrangian assimilation methods developed during the previous grant period have been applied to the assimilation of Argo float trajectories in an operational oceanographic model of the Mediterranean Sea (MFS, Mediterranean Forecasting System). For the first time, both ARGO trajectories and vertical profiles together with satellite data have been assimilated using a 3D-var scheme to produce analyses for short term forecasts (Taillandier et al., 2009). The study period covers three months during winter 2005 when four ARGO trajectories were present in the north western Mediterranean Sea (Fig.1).

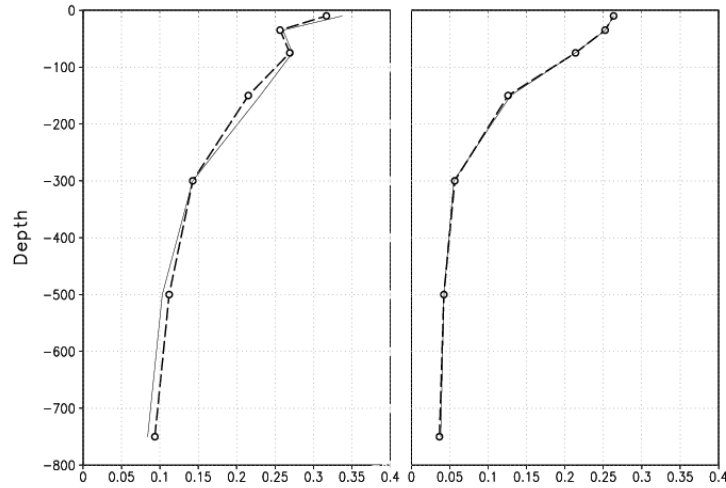
The impact of the trajectory assimilation have been tested with two main goals: a) to verify that the trajectory assimilation is consistent with the assimilation and dynamics of the other mass variables of the model, b) to investigate the specific impact of trajectory assimilation on the regional prediction.

As a first step the question of internal consistency has been considered testing whether or not the trajectory assimilation alters the misfits with respect to the mass variables. This is a relevant and non-trivial question. Given the great number of scales and processes present in the ocean, data compatibility is not always guaranteed, especially for drift related quantities that sample all the scales of motion and are directly affected by ageostrophic processes. Indeed, the question of “representativeness”, i.e. spatial and temporal variability of the measured quantities with respect to the scales of the analysis, is one of the great challenges faced by operational oceanography. The results of the analysis show that the trajectory assimilation, while improving the drift misfit, does not deteriorate the analysis of the ARGO TS (Temperature and Salinity) profiles, as shown by the misfits in Fig.2. This indicates that the Lagrangian data assimilation, at least for ARGO floats, is consistent with respect to the mass variables.

A set of diagnostics is then performed, including hydrological sections, transport, mean circulation and variability, aimed at quantifying the impact of trajectory assimilation. Given the reduced number of independent data available, most of the analysis is performed comparing results obtained with



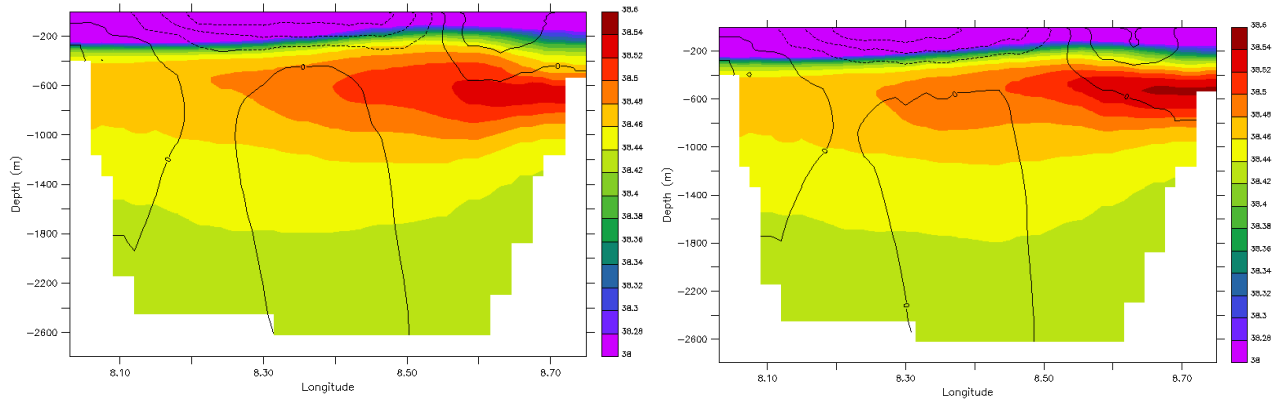
**Figure 1: Trajectories of four ARGO floats in the NW Mediterranean. The two sections of the Balearic Sea and Ligurian Sea are also indicated as straight lines superimposed on the isobaths 500m, 1000m, 2000m.**



**Figure 2: The root mean square of temperature misfits ( $^{\circ}\text{C}$ , left panel) and salinity misfits (PSU, right panel) in the period January-March 2005 for the four ARGO floats in the NW Mediterranean. The full line represents the result in OSref (without trajectory assimilation), and the dashed line in OStrj (with trajectory assimilation).**

trajectory assimilation (OStraj run) and without trajectory assimilation (OSref run) and considering a qualitative assessment with respect to historical data.

The results suggest that the analysis with trajectory assimilation provides a more accurate description of the boundary currents sampled by the ARGO trajectories, that are not fully resolved by the other components of the observing system. An example is shown in Fig.3 for the Ligurian Sea section. A core of maximum salinity in subsurface, which characterizes Levantine Intermediate Waters (LIW), is well marked in the two analyses, situated along the western Corsica Current and directly sampled by two floats (Figure 1). The vein delimited by the isohaline 38.52 PSU (in dark red color) appears located between 600m and 800m deep in OSref (i.e. without trajectory assimilation, Figure 3 left panel), and between 400m and 700m deep in OStrj (i.e. with trajectory assimilation, Figure 3 right panel). Moreover, this vein of LIW is located within the core of the boundary current flowing northwestward in Ostrj, while in Osref is deeper than the boundary current and located at a more quiescent depth. The pattern depicted by Ostrj appears more realistic, given that historic measurements suggest that a persistent branch of LIW tends to follow the coastal pathway along the western coast of Corsica, without penetrating the interior (Millot, 1999).



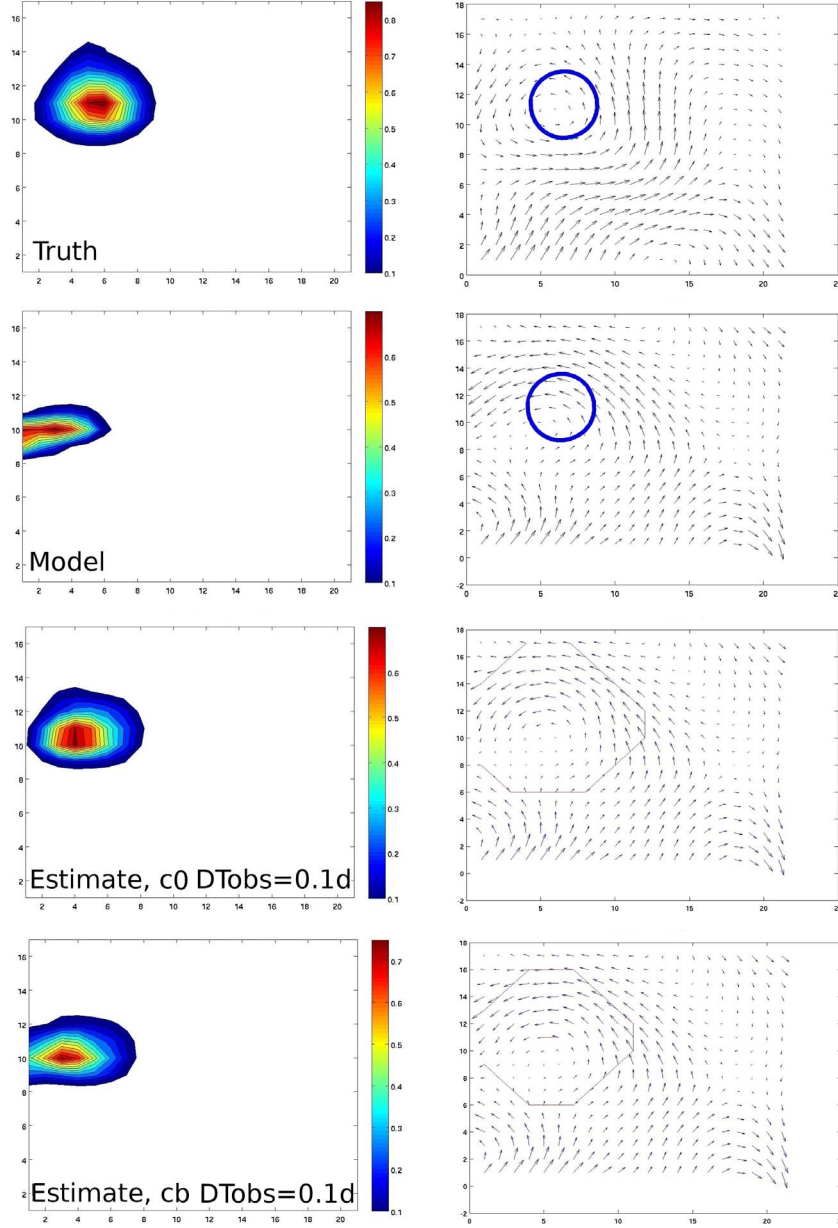
**Figure 3: Mean stratification along the section of the Ligurian Sea. Salinity (in PSU) extracted daily in the first 600m from the analysis OSref (OStrj), in left (right) panel and averaged during the period January 1 – March 31, 2005. Contours: absolute velocities normal to the section (in cm/s, every 5cm/s) averaged over the same period.**

#### *ii) Velocity estimation using fusion of surface tracer data and circulation model outputs*

In a recent paper, Piterbarg (2009) has developed a simple method based on the fuzzy set theory (fuzzy logic, see e.g. Dubois et al, 1997) to attack the problem of estimating surface ocean velocity using surface tracer data from satellite and circulation model outputs. The method relies on the use of image sequences where the tracer (or its proxy) is assumed to be transported by the currents and to obey a known equation such as the advection-diffusion equation in two dimensions. In this setting, the main challenge is represented by the fact that while the cross-gradient velocity information can be retrieved from the tracer distribution at subsequent times, the along-gradient component cannot be directly inferred. The method uses the information from the circulation model to remove the uncertainty of the along-gradient velocity, and it includes a tracer equation with sources and sinks in addition to the basic advection and diffusion. In the simplest case, when sources and sinks are zero or assumed known, the along-gradient velocity simply coincides with the model estimate.

The method has been tested in a joint work with L. Piterbarg (Mercatini et al., 2009) using the classical ‘twin experiment approach’ (Molcard et al., 2003; Taillandier et al., 2006) in the framework of a

realistic operational model of the Mediterranean Sea (MFS, Mediterranean Forecast System). A sequence of daily velocities from MFS starting from a given date are regarded as the ‘Truth’, and the synthetic tracer is released in it and ‘observed’. An other sequence, starting from a different date is

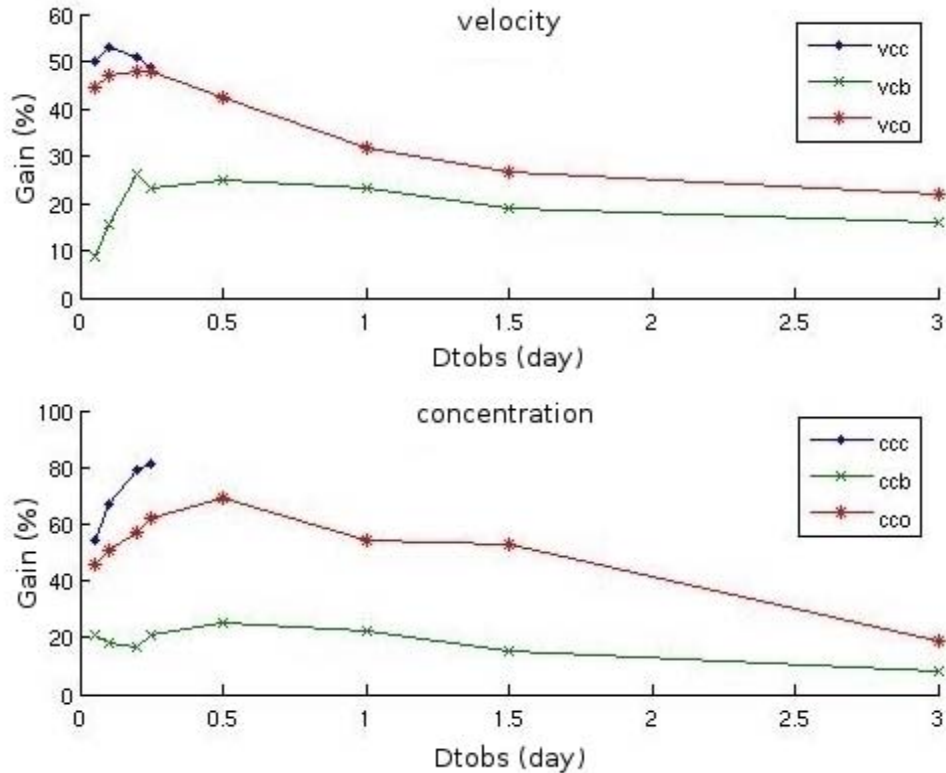


**Fig.4** Examples of velocity (right panels) and tracer (left panels) estimation. The Truth (upper), the Model (middle upper), and two types of estimates for  $Dt=1$  day are shown. The two estimates correspond respectively to modality CC (tracer information available inside the patch, lower middle) and modality CB (information available only on the patch boundary, lower). The blue circles indicate the release area of the patch, and the red lines indicate the area where the estimate correction is active.

regarded as the ‘Model’ and it is used in the estimation together with the observations. The specific configuration that we consider consists in releasing a localized tracer patch and advecting it in the flow field. The configuration is motivated by the practical application of a pollutant released from a source, such for instance an oil spill, observed by visible, infrared or microwave satellite sensors. An extensive sensitivity study is performed, varying the interval  $Dt$  between successive information in a realistic

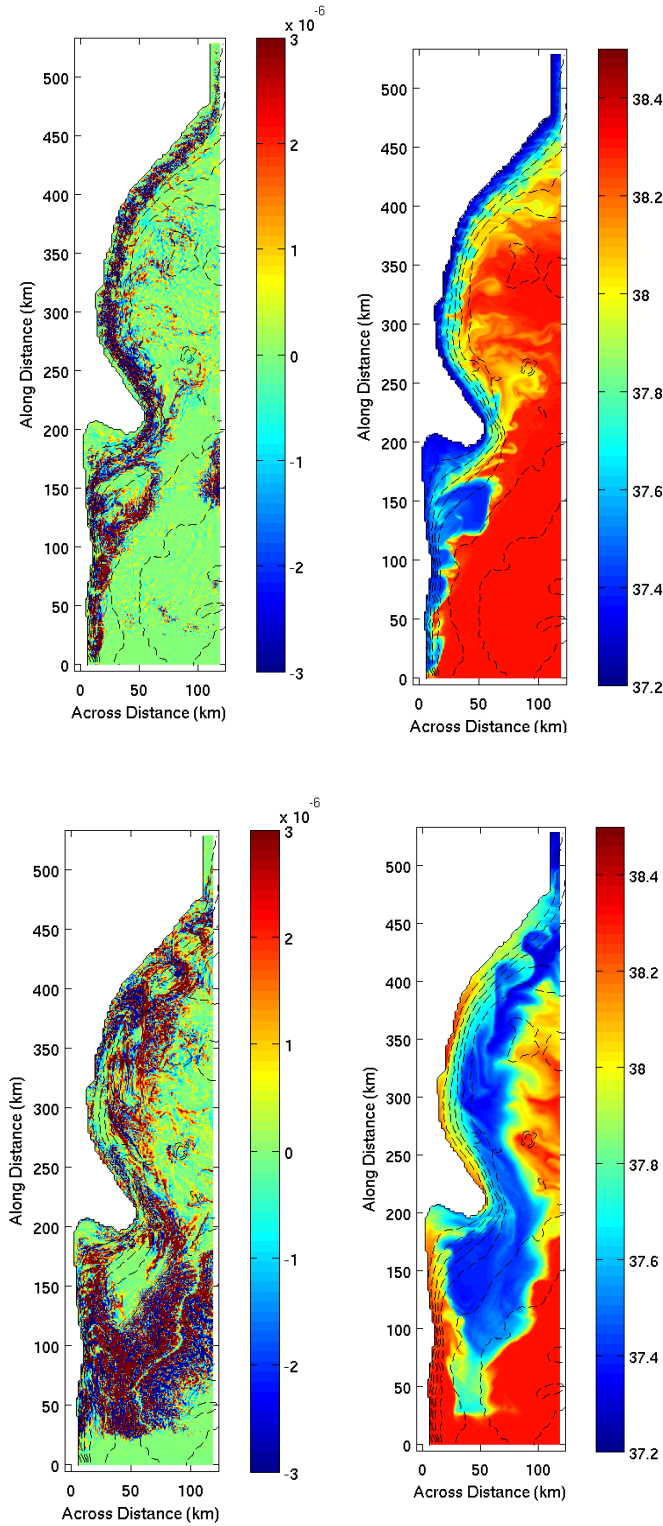
manner, and considering degradation in the quality of the data going from idealized perfect data to reduced data describing only the patch boundaries. Also the time and space variability of the applications, and the dependence on the parameters of the patch are considered.

An example of results for a realistic  $Dt$  of 1 day is shown in Fig.4, displaying concentration and velocities for the Truth (upper panels), the Model (upper middle panels) and the estimate for two different types of information; CC (lower middle panels), corresponding to complete tracer information inside the patch, and CB (lower panels) corresponding to the more realistic case when only the boundary of the patch is observed. The correction appears effective, especially for CC but also for CB, as it can be seen comparing visually the estimated concentration and velocity fields with the truth and models ones.



**Fig.5 Plots of Gain versus time interval between observations,  $DT$ , for the estimates with respect to model results. The Gain for velocity is shown in upper panel and for concentration in lower panel.**

**Blue lines indicate results obtained in modality CA (complete tracer information), red lines in modality CC (tracer information inside the patch) and green lines in modality CB (information on the patch boundary only).**



**Fig.6** Surface fields illustrating the instabilities of a buoyant current with different wind forcing, from numerical simulations of an idealized Western Adriatic Current (WAC). Upper panels are for northern wind (downwelling prone and down front), while lower panels are for southern wind (upwelling prone and up front). Left panels show the baroclinic conversion term  $Cbcl$ , right panels the salinity.



A more quantitative assessment of the method is shown in Fig.5, where the ‘Gain’, i.e. the improvement in accuracy of the estimates with respect to the Model, is shown for velocity (upper panel) and concentration (lower panel) versus  $\Delta t$  and for 3 different observation modalities: CC, CB (described before) and CA, corresponding to the ideal case of perfect observations over the whole domain. The general behaviour of the Gain shows that the estimation skills decrease as the information deteriorate, i.e. at increasing  $\Delta t$  and going from CA to CB, as can be expected. The improvements range from approximately 80-90% for concentration and 50-60% for velocity in the case of almost perfect data, to values of 30-40% for realistic time intervals of the order of days and reduced tracer information, and values of 15-20% when only the boundary of the patch is observed. The results are found to be robust to flow variability and patch parameters.

### *iii) Investigation of upper ocean coastal buoyant fronts*

Understanding the dynamics of coastal fronts and their instabilities is central for a correct modellization and prediction of coastal flows. In particular, understanding the size and nature of the involved scales is very relevant for assimilation and fusion, since it provides guidance on the choice of the relevant scales and of the necessary resolution for numerical models and observations.

In a recent paper (Magaldi et al., 2009), the dynamics of a coastal buoyancy front in presence of wind forcing and complex topography have been studied, considering an idealized model of the Western Adriatic Current (WAC). Data from a recent international experiment lead from NURC and NRL, the DART experiment, have been used to set up the main parameters of the numerical simulations. The instabilities of the buoyant current have been quantified computing the baroclinic conversion term,  $C_{blc}$ , and calculating the impact of instabilities in terms of bulk quantities such as mixing or transport in the basin.

In absence of wind, the Adriatic Promontories force the current to separate from the coast and induce instabilities. Persistent downwelling favourable winds (Fig. 6, upper panels), blowing ‘down front’ from the north, tend to thicken and narrow the currents, generating small scale instabilities (less than 10 km) that tend to subside on time. On the contrary, upwelling favourable winds (Fig.6, lower panels), blowing up front from the south, tend to thin and widen the current, generating larger and rapidly growing instabilities (order of 35 km) that destabilize the current. When realistic winds are considered, the same trends are observed, but the state of the sea set up by previous wind events also plays a crucial role.

## **IMPACT/APPLICATIONS**

The results on Lagrangian data assimilation and fusion have a significant impact for operational systems and they provide additional value to data from floats, drifters, satellites and gliders especially for coastal applications. The numerical results on the coastal front instabilities provide information on the main space and time scales of the flow, therefore providing guidance for numerical resolution and measurement requirements.

## TRANSITIONS

The application of the Lagrangian data assimilation method to the assimilation of subsurface ARGO floats is presently transitioned to the operational Mediterranean Forecasting System (MFS) in collaboration with N. Pinardi (INGV).

## RELATED PROJECTS

Predictability of particle trajectories in the ocean, ONR, PI: T.M. Özgökmen, N00014-05-1-0095.  
Statistical and stochastic problems in Ocean Modeling and Prediction, ONR, PI: L.Piterbarg, N00014-99-1-0042.

## REFERENCES

Dubois, D., Prode, H., Yager, R.R. 1997. Fuzzy Information Engineering. John Wiley & Sons, Inc

Magaldi M.G., T.M. Ozgokmen, A. Griffa, M.Rixen, 2009. On the response of a turbulent coastal buoyant current to wind events, *Ocean Dynamics*, submitted

Mercatini A., A. Griffa, L Piterbarg, E. Zambianchi, M. Magaldi. Estimating surface velocities from satellite data and numerical models: implementation and testing of a new simple method, *Ocean Modelling*, submitted

Molcard, A., Piterbarg, L.I., Griffa, A., Ozgokmen, T.M., Mariano, A.J., 2003. Assimilation of drifter positions for the reconstruction of the Eulerian circulation field. *J. Geophys. Res.* 108, 3056.

L.I. Piterbarg, 2009: A simple method for computing velocities from Tracer observations and a model output. *Appl. Math. Modell.* 33, 3693-3704

Taillandier, V., Griffa, A., Molcard, A., 2006. A variational approach for the reconstruction of regional scale Eulerian velocity fields from Lagrangian- data. *Ocean Modelling.* 13(1), 1-24.

Taillandier V., S. Dobricic, N. Pinardi, P. Testor, A. Griffa, L. Mortier, G.P. Gasparini, 2009. Integration of ARGO trajectories in the MFS assimilation scheme, and impact on the regional analysis of the North Western Mediterranean circulation *J. Geophys. Res.*, submitted and revised

## PUBLICATIONS (2008-2009)

Taillandier V., A. Griffa, P.M. Poulain, R. Signell, J. Chiggiato, S. Carniel, 2008: Variational analysis of drifter positions and model outputs for the reconstruction of surface currents in the Central Adriatic during fall 2002. Submitted to *J. Geophys. Res.* 113, C04004, doi.1029/2007/JC004148 [published, refereed].

Magaldi, M., T.M. Ozgokmen, A. Griffa, E. Chassignet, M. Iskandarani and H. Peters, 2008: Turbulent flow regimes behind a coastal cape in a stratified and rotating environment. *Ocean Modelling*, 25, 65-82 [published, refereed].

Molcard A., P.M. Poulain, P. Forget, A. Griffa, Y. Barbin, J. Gaggelli, J.C. De Maistre, M. Rixen. 2009. Comparison between VHF radar observations and data from drifter clusters in the Gulf of La Spezia (Mediterranean Sea), *J. Mar. Sys.* Doi:10.1016/j.jmarsys.2009.01.012 [published, refereed].

Magaldi M.G., T.M. Ozgokmen, A. Griffa, M.Rixen, 2009. On the response of a turbulent coastal buoyant current to wind events, *Ocean Dynamics*, [submitted, refereed].

Mercatini A., A. Griffa, L Piterbarg, E. Zambianchi, M. Magaldi, 2009. Estimating surface velocities from satellite tracer data and numerical models: implementation and testing of a new simple method, *Ocean Modelling*, [submitted, refereed].

Taillandier V., S. Dobricic, N. Pinardi , P. Testor, A. Griffa, L. Mortier, G.P. Gasparini, 2009. Integration of ARGO trajectories in the MFS assimilation scheme, and impact on the regional analysis of the North Western Mediterranean circulation *J. Geophys. Res.*, . [submitted, refereed].